

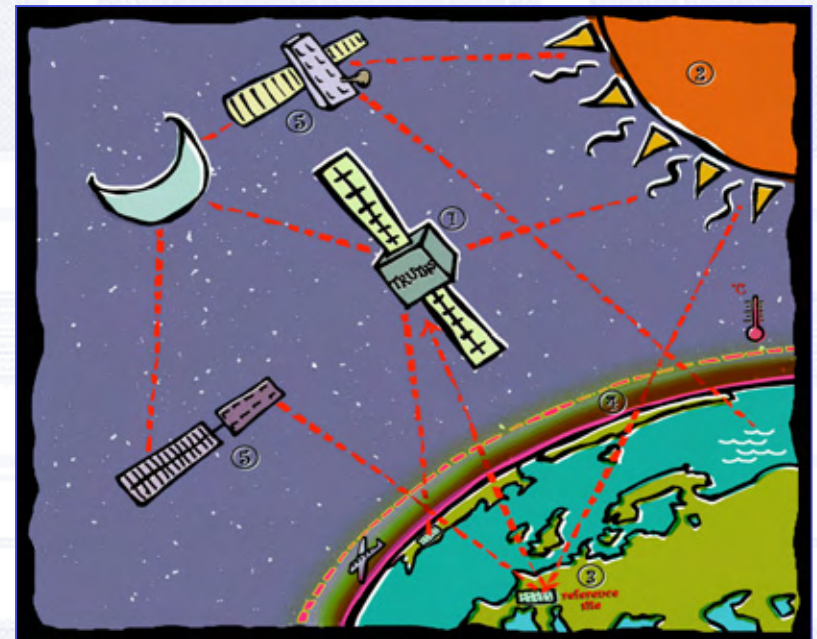
TRUTHS: a component of an “international calibration constellation” to meet the needs of climate

Nigel Fox

Optical Technologies and Scientific
Computing Tm

Quality of Life Division

CLARREO workshop



TRUTHS

Traceable **R**adiometry **U**nderpinning **T**errestrial- & **H**elio- **S**tudies

Nigel Fox **NPL**

Nigel.Fox@npl.co.uk

James Aiken **Plym Mar Lab**

Xavier Briottet **ONERA**

John Barnett **Ox univ.**

Steve Groom **Plym Mar Lab**

Claus Frohlich **PMOD/WRC**

Jo Haigh **Imp Coll**

Olivier Hagolle **CNES**

Hugh Kieffer **USGS**

Judith Lean **NRL**

John Martin **NPL**

David Pollock **U of Alab.**

Mike Sandford **RAL**

Michael Schaepman **U of Zur**

Werner Schmutz **PMOD/WRC**

Keith Shine **Uni of Read**

Phil Teillet **CCRS**

Theo Theocharous **NPL**

Kurtis Thome **U of Ariz**

Terry Quinn **BIPM**

Michel Verstraete **JRC(Italy)**

Emma Woolliams **NPL**

Ed Zalewski **U of Ariz**

Need for improved Quality Assurance: solar spectral domain

Difficulties

- Bias between sensors

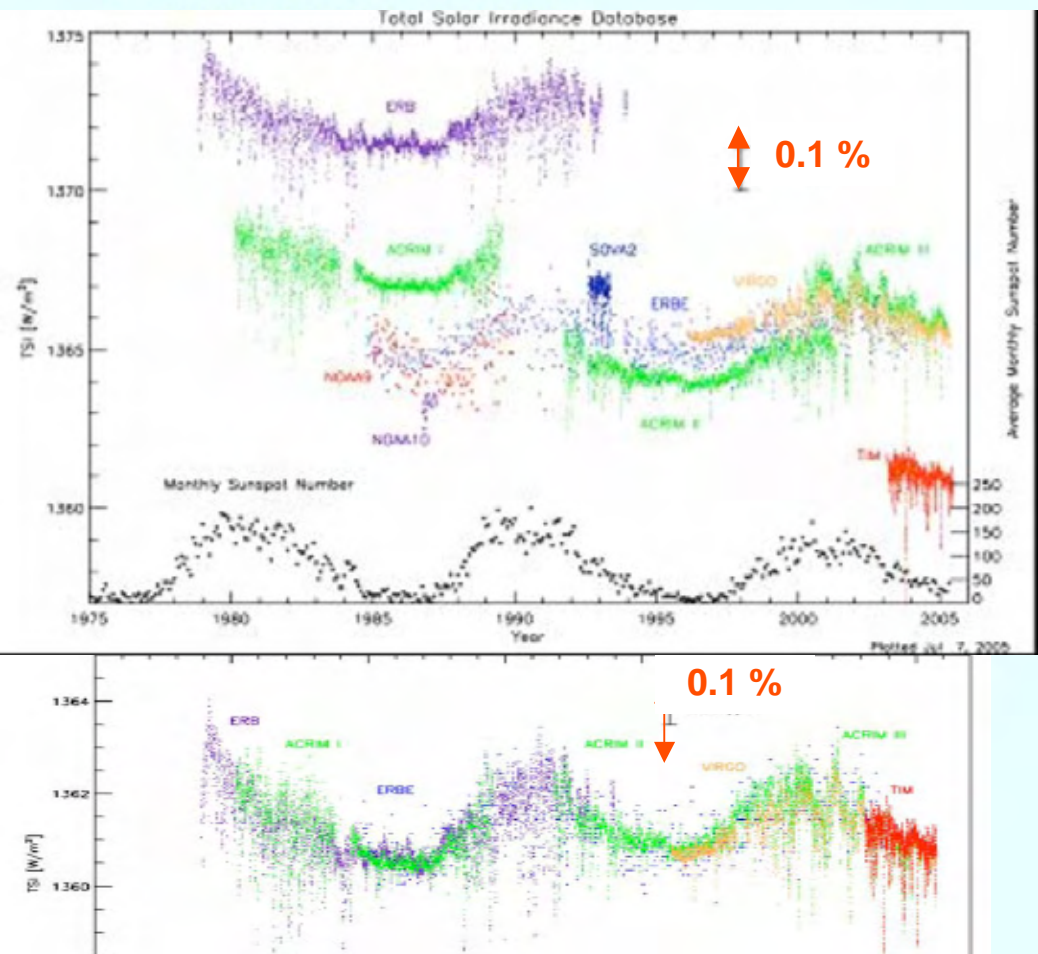
Requirement

Typical Instrument R

All data from instrument calibration

From: Hugh Keiffer USGS

- LandSat 5 TM. 19 years
 - Bands 1,2,3,4,5,7: ~23,17,11
 - Bands 5 and 7: 5% peak-to-peak
 - LandSat 7 ETM+. All bands ~2
 - SeaWiFS. VIS <2% in 5.7 years
 - MODIS. Terra: 1 to 8% in first
 - Aqua: ~-0.4% in 60 da
 - MISR. Initial drop ~6%, then 1
 - ALI. From -18% to +5%. Ther
 - Hyperion. Initial:-8% VIS, -18%
 - SPOT-5. Pre-Launch to Orbit:
 - ASTER. VIS 8 to 20% in 2 year
- debate.



Reliable satellite data quality

Ideally Requires:

Pre-flight instrument design conformance

Traceable sub-system characterisation/calibration

“ End-to-end calibration

Maintenance/life-test of witness samples/sub-systems

Post-launch design/performance conformance

Traceable calibration/validation of all key characteristics

- on-board calibration system!
- comparison with physical parameter
- “ with reference data/instrument
(comparison with existing similar instrument)

CEOS WGCV recommendation endorsed by CEOS plenary 19

Background

CEOS WGCV notes the growth in number of optical satellite sensors, and the diversity of their spectral and spatial characteristics. It notes that these sensors have been deployed, to meet the needs of both scientific and commercial applications and that the near “operational nature” of data provision from such sensors means that increasing reliance is put on the integrity and reliability of EO data, by governments, international agencies and the commercial sector.

+ ... problems with stability, bias and need to combine data etc and the strategy document of the WMO (now GSICS).....

WGCV recommends that CEOS agencies ensure that all satellite pre-flight calibration activities should include not only an “end to end” system calibration but also of all appropriate sub-system components, and that these should all be made demonstrably traceable to SI units.

CEOS agencies should be encouraged to use SI traceable “benchmark” radiometric reference targets viewable by space based EO sensors to unequivocally quantify and remove biases between optical sensors. Such targets would probably include the Moon, Sun and a number of ground sites e.g. Deserts used by existing missions.

..... Post launch requirements include:

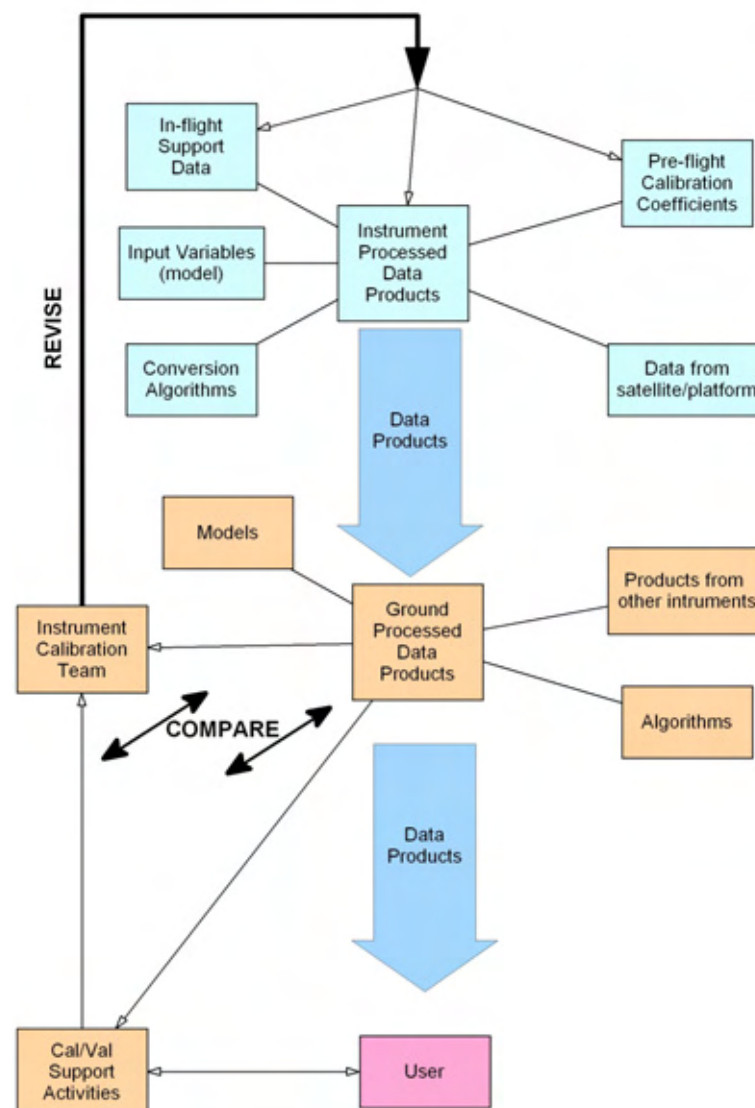
Options

- Provide link to SI via a sub-set of instruments flown to simultaneously view same target as satellite
 - high altitude aircraft, Balloon, Rocket, Shuttle, ISS
 - degradation/outgassing, multiple targets, range of parameters
- Vicarious calibration via calibrated reference targets
 - Desserts, Moon, Stars, Snow fields
 - Maintenance/establishment of radiometric accuracy
- Designation of one or group of instruments as “reference”
 - Rely on mission overlap for traceability continuity
 - Which one ? Improved calibration/reliability ? Degradation
- Dedicated International Calibration mission – “Std Lab in-orbit”
 - Optimised calibration system, international agreement, long-term reliability, mimic terrestrial systems, (could additionally do science!!)
 - Cost, Degradation? Traceability? Accuracy?
 - Transference to other missions
 - Improve atmospheric correction models

-From CEOS strategy document for GEOSS (2005)

Validated data products require all processing steps and data to be QA – Accredited?

- Pre-flight
 - User specification
 - Instrument build compliance
 - Calibration?
- Post-launch
 - In-flight checks
 - Ground “Truth” comparison
 - Inter-sensor cross calibration
- Processed data released
 - “validated”
 - Uncertainty statement?



Infrastructure for innovation in measurement, validation and QA of EO data



- Transfer standards
- Comparisons
- Innovation on techniques
- Measurement & test protocols
- International link
- Independence

Modelling & Data processing



QA

Traceability

Audit

Validation

Calibration

Academia

Advice

Public sector

Private Industry



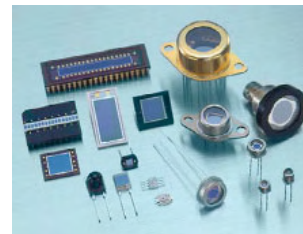
Radiometric traceability

SI



Cryogenic Radiometry

~0.01 %



Spectral Responsivity

~0.1 %



Appearance



Photometry

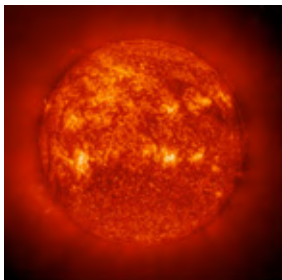
Spectral radiometry



~0.5 %



Pyrometry



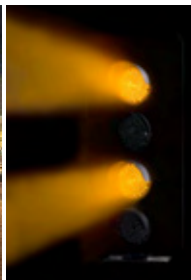
Solar



Remote Sensing



Lighting



Transport



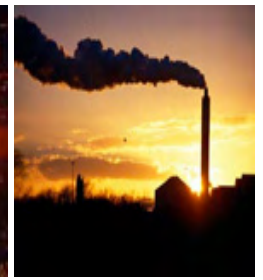
Aerospace



Medicine

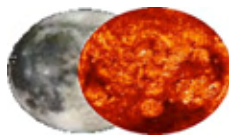
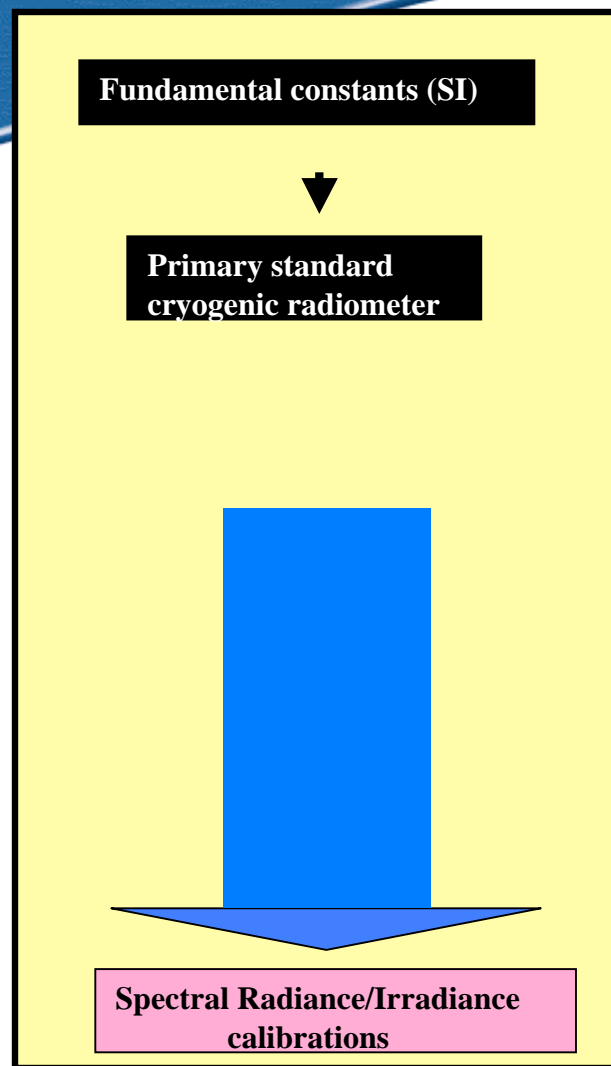


Industry

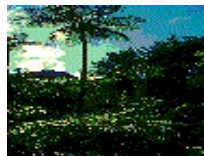


Environment

Traceability for Optical radiation measurements



Extra-Terrestrial



LAND

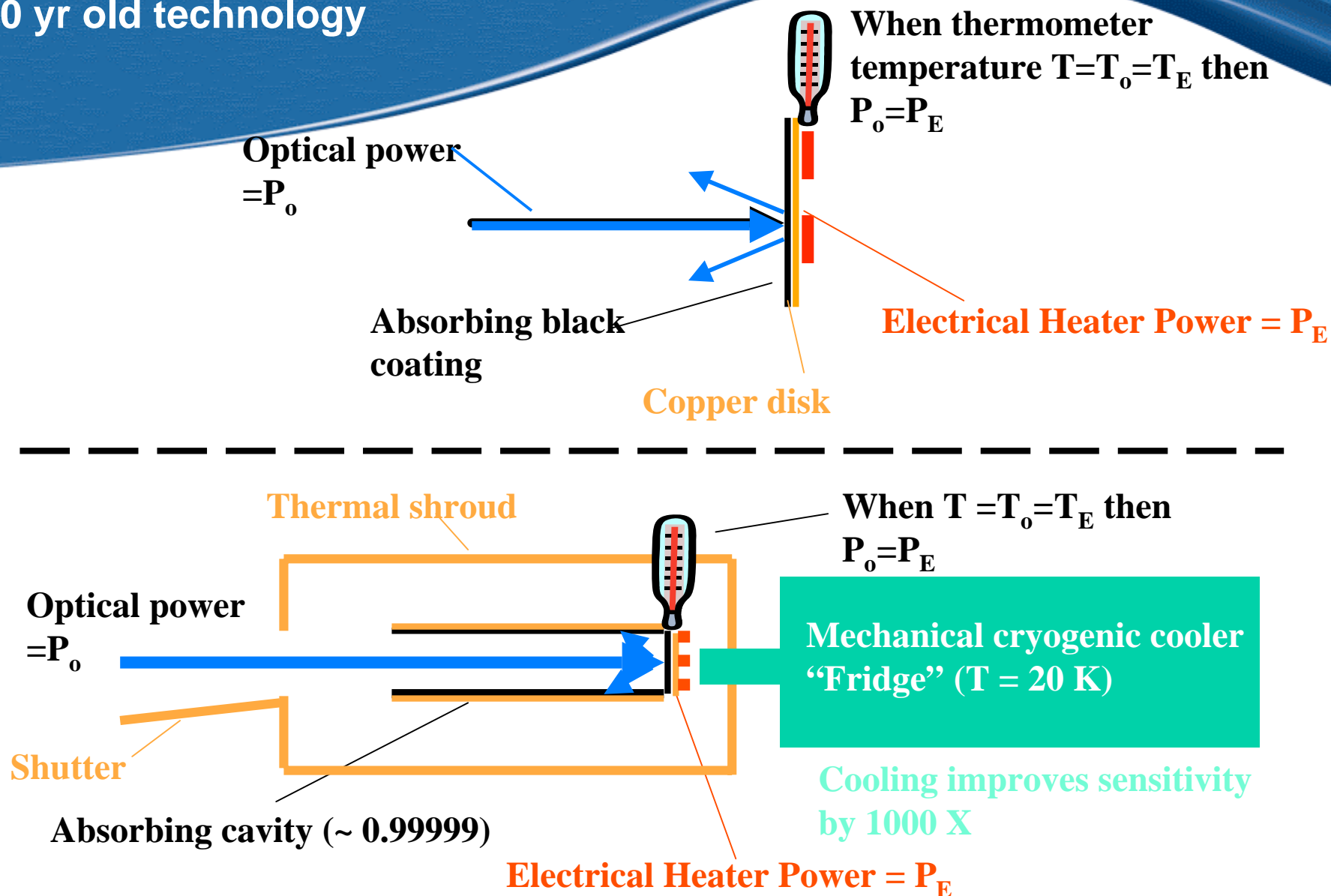


OCEAN



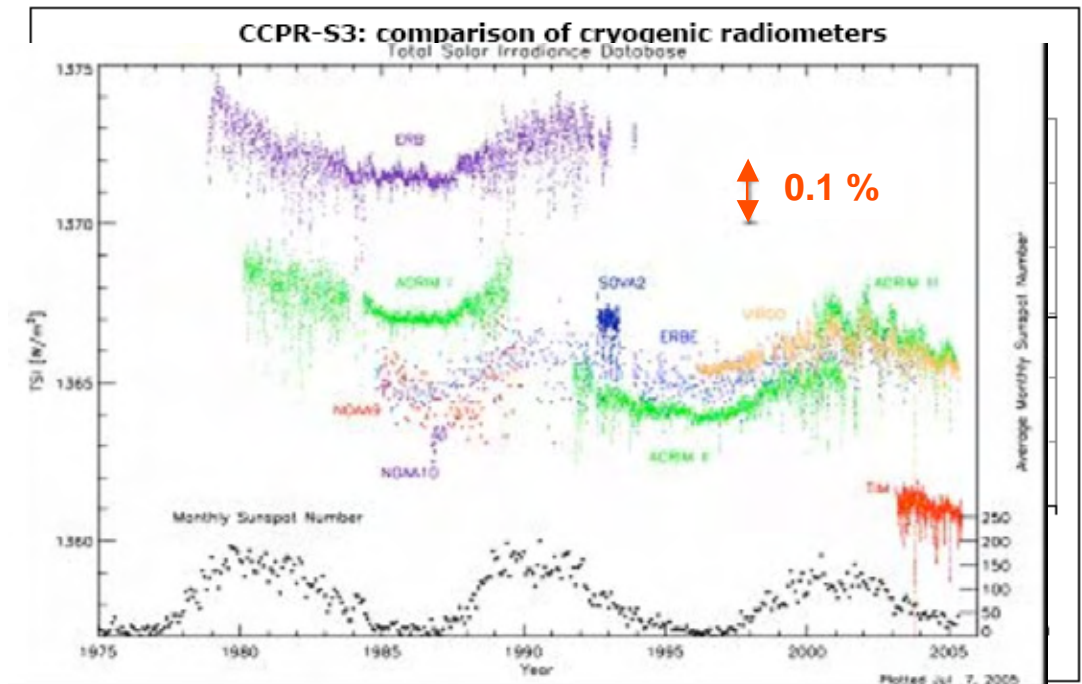
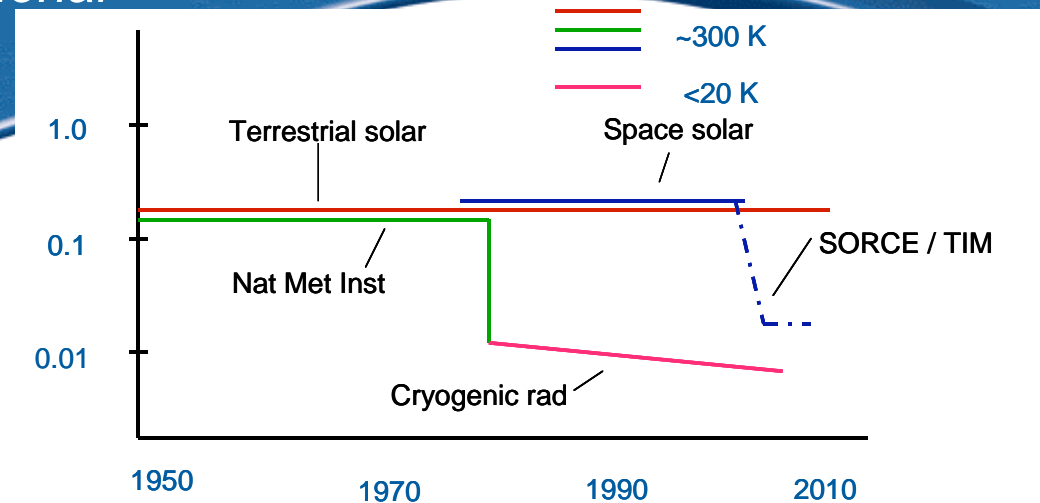
ATMOSPHERE

Electrical Substitution Radiometry - a 100 yr old technology



Cryogenic Radiometry – *international agreement and consistency*

- High diffusivity
 - potential of large cavity, (high absorptance)
 - rapid isothermal conditions
 - controlled heat flow paths
 - Superconductive leads
 - no joule heating loss
- High sensitivity thermometry
- Stable thermal environment
 - low external load (background)
 - low cavity radiative loss



Fundamental constants (SI)

Primary standard
cryogenic radiometer

Laser
Cal interval ~100nm

Photodiode
(spectral responsivity)

Laser
Cal interval ~0.1 nm

Filter Radiometer

Radiance Temperature

Ultra High Temperature
Black Body (3500 K)

Radiance continuum
(Planck)

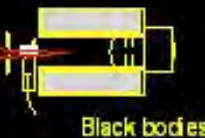
Spectroradiometer
(multi-band filter radiometer)

Spectral Radiance/Irradiance
calibrations



National Laser Radiometry Facility
(NLRF)
or SIRCUS

Continuously tuneable CW laser
radiation from 210 nm to 11 μm power
stabilised <0.001% drift



Accuracy ~ 0.02%

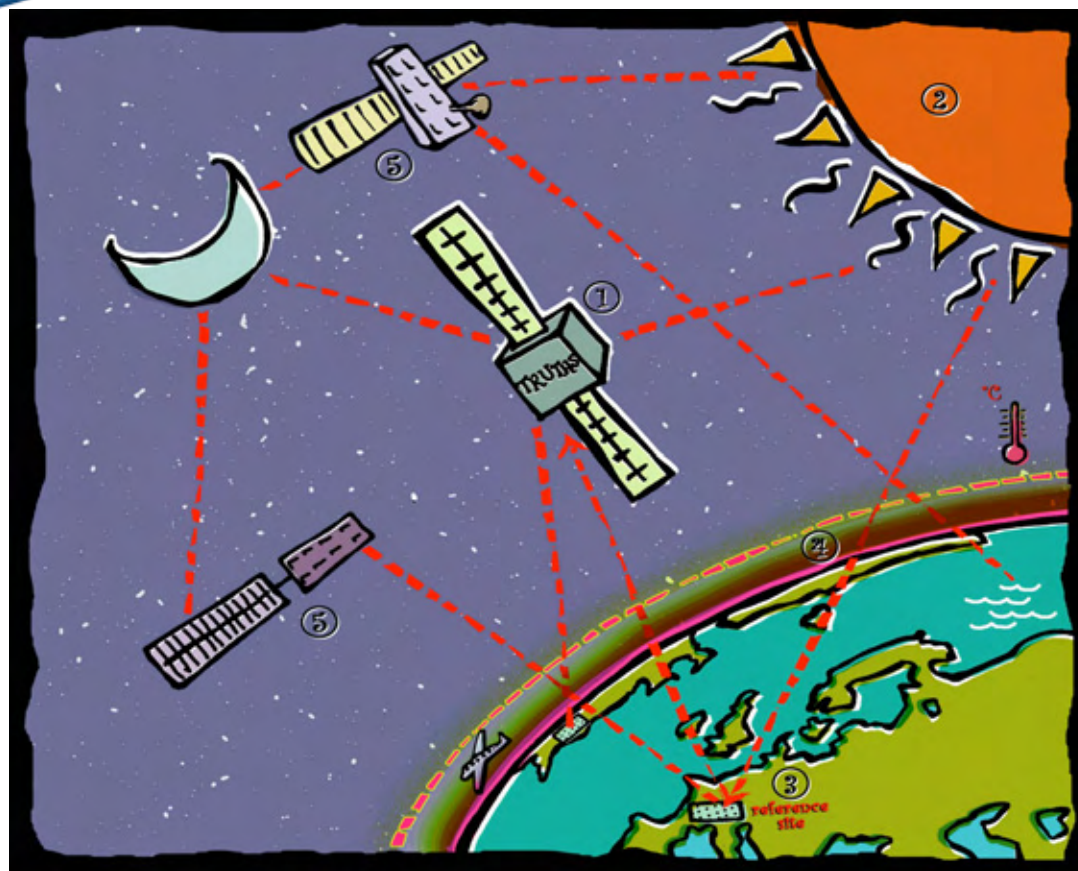


Extra-Terrestrial

TRUTHS: Traceable Radiometry Underpinning Terrestrial- and Helio- Studies

Satellite based mission to:

- make SI traceable high accuracy measurements of solar radiation incident on, and reflected from, the Earth
- transfer its unprecedented calibration accuracy to other satellite-based EO instruments through the calibration of reference targets such as the Sun, Moon and the Earth's deserts
- Supporting measurements of land processes, ocean colour, Earth radiation budget, atmospheric chemistry and aerosol distribution



Earth/Moon viewing

- Wide spectrum (380 to 2500 nm)
 - Spatial resolution ~ 25 m (multi-angle)
 - Spectral radiance uncertainty <0.5% (using novel in-flight calibration system)
- baseline

Geophysical parameters measured by TRUTHS (baseline)

Measurand	Spectral resolution nm	Spatial resolution m	Accuracy %
Total Solar Irradiance	Total	-	0.01
Solar Spectral Irradiance	200 – 2500 (0.5 - 1)	-	0.1
Lunar Spectral Irradiance and Radiance	380 – 2500 (10)	-	<0.5
Earth Spectral Radiance (Polarised and Non-pol) <i>multi-angle</i>	380 – 2500 (10 nominal)	~ 25 (TBD) (20 x 20 km) <i>for optimisation</i>	<0.3
<i>via filter rads for Aerosols / E Rad Budget</i>	TBD	20 km (TBD)	<0.3

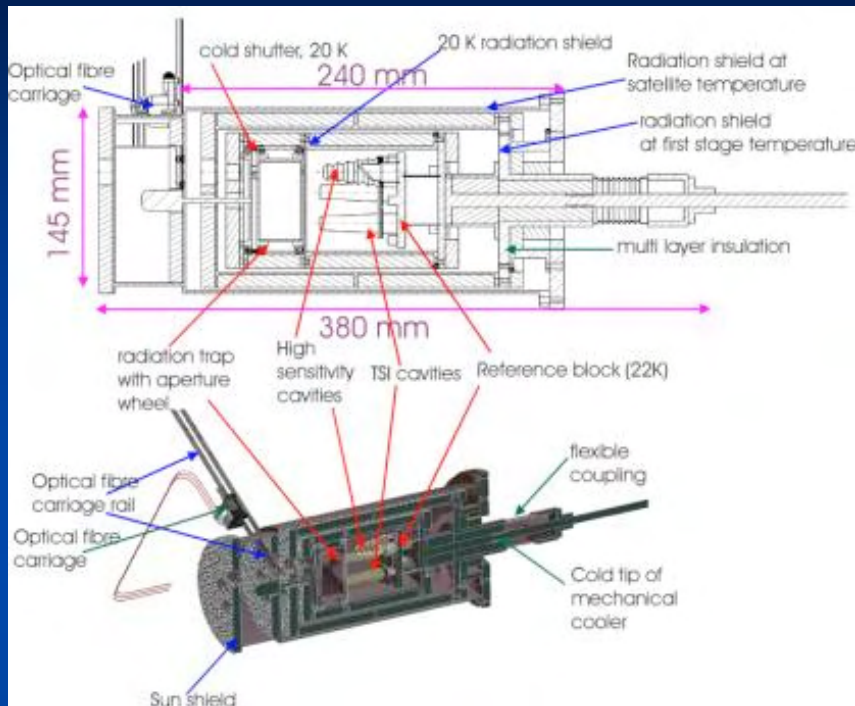
Optional orbit for consideration

Oblique angle away from pole:

- fewer repeats
- more satellite coincidences

- orbiting accuracy = 0.5 km (knowledge ~ 10 m)

Cryogenic Solar Absolute Radiometer



Use of electrical substitution makes traceability to SI through convenient electrical units – optical interface via black cavity absorber, coated with ‘NPL super-black’ Solar weighted absorptance >0.99998 .

CSAR cooling from Astrium 20 K cooler

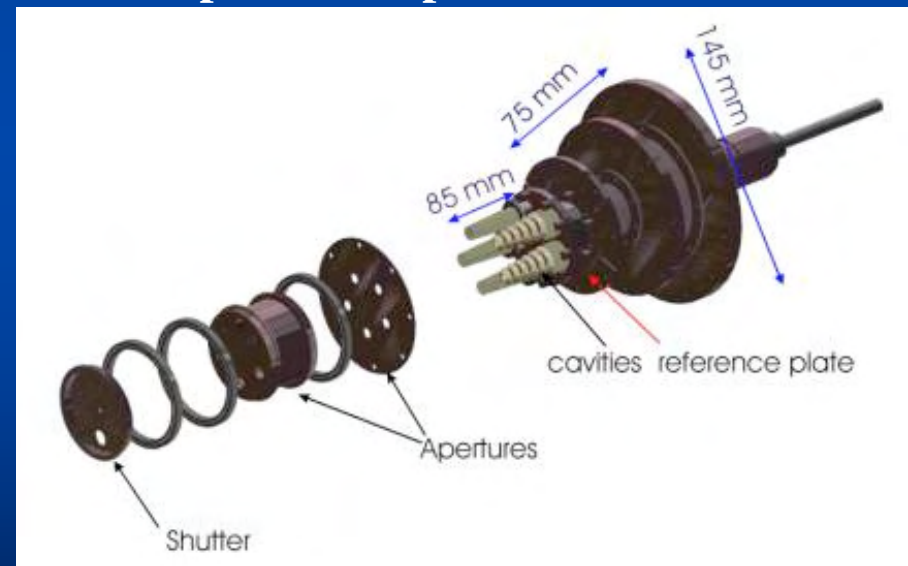
3 cavities for TSI – $t \sim 15$ s

- operating range 10 mW to 100 nW

2 cavities for spectral response – $t \sim 0.5$ s

- operating range 0.1 mW to 10 nW

3 off 5 mm precision apertures + 2 off 0.5 mm



Under development

Calibration summary

All measurements traceable to SI through CSAR in space (as on ground)

- Cavity absorptance only optical interface not calibrated in flight
 - multiple cavities for redundancy

(factor of 1000 degradation = 1 % uncertainty)
- Electrical power is link to SI
- Geometry (apertures) multiple and changeable for redundancy
- Wavelength of spectrometers checked with fraunhofer lines and low power laser diode
- Secondary standards only exposed to low power spectrally dispersed radiation

Imager calibration via filter radiometers

- simultaneous viewing of on board sun illuminated diffuser (multiple illum angles)
- “ “ of external target – Moon, Land, Cloud ...



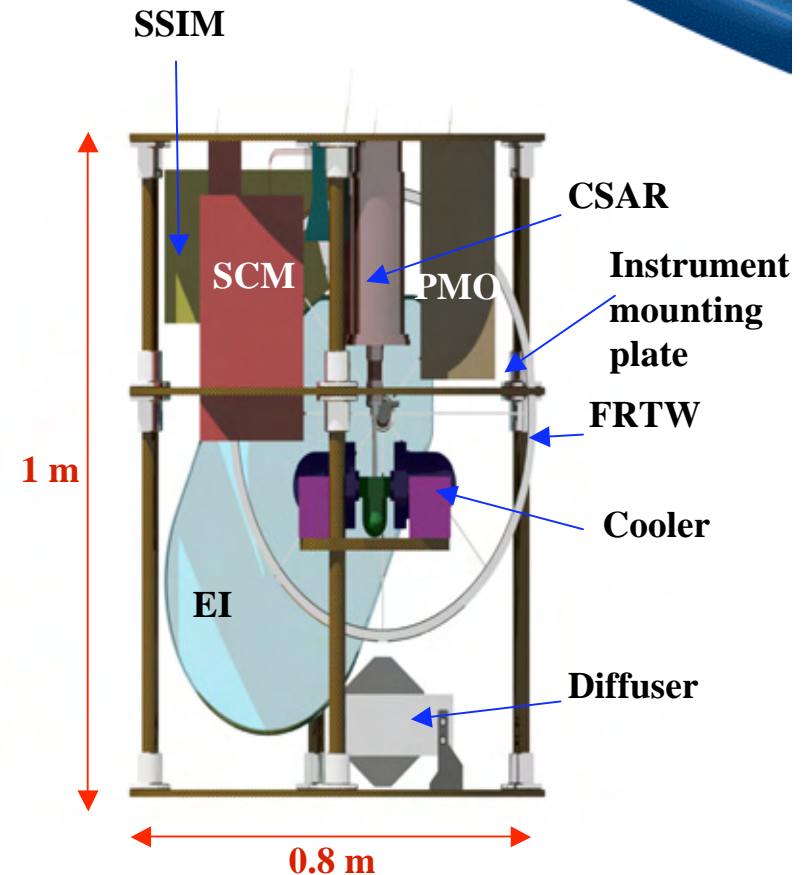
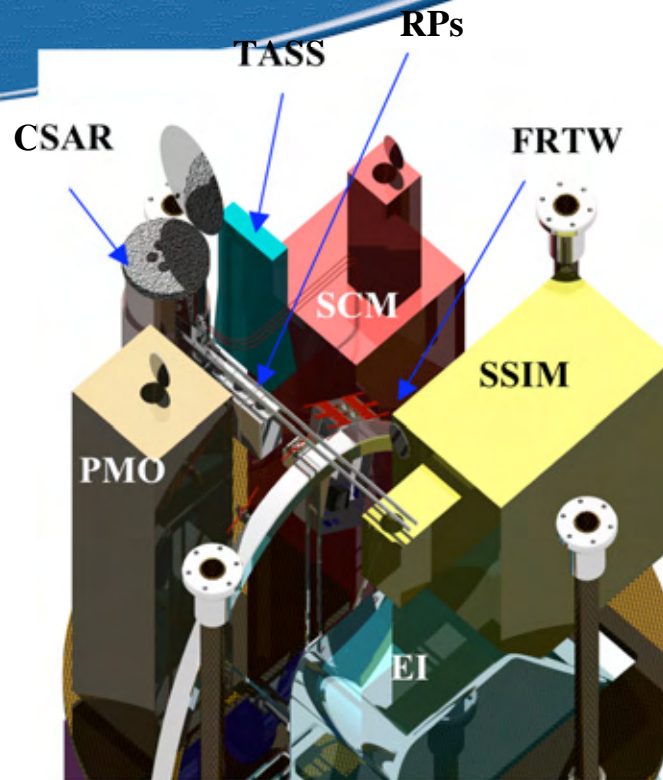
(provides some mission redundancy if imager fails and linearity checks)

Instrument integration on Truths satellite (baseline, other than calibration system all are TBD)

Payload:

Mass = 130 kg

Power = 185 W



Solar: Cryogenic Solar Absolute Radiometer **CSAR**

- TSI, Primary standard

WRC PMO ambient temperature radiometers **PMO** - TSI

Solar Spectral Irradiance Monitor **SSIM**

- SSI

Earth: Earth Imager (spectrometer) **EI**

- Spectral radiance

NPL Polarised Filter Radiometers **PFR**

- Polarised spectral radiance

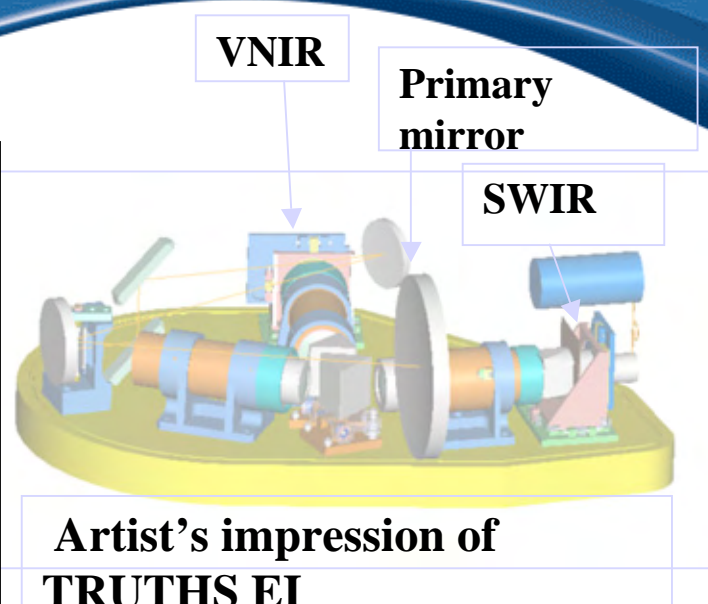
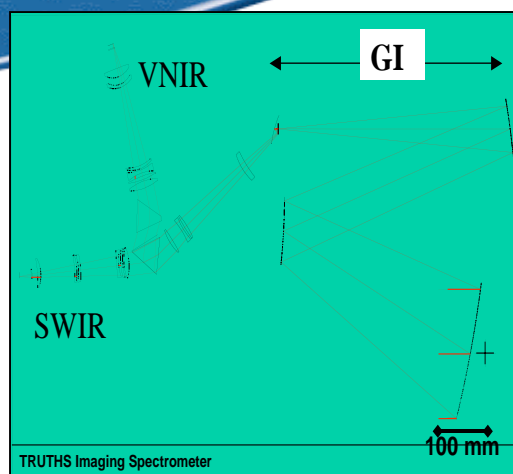
TRUTHS Earth Imager (baseline)

**Hyperspectral and high spatial to
simplify matching to other sensors**

Based on 1024 pixel detector

- 20 m at 20 km swath
- 100 m at 100 km swath

Could use 4000 pixel device
(IATA?)



*** Prism based spectrometer**
(grating or FT)

*** 212 channels nominal 10 nm bandwidth (1 to 8 nm)**
(not all bands need to be used all the time)

*** 200 mm diameter primary mirror** *** 380 to 2400 nm**

*** 20 m ground resolution** *** Data rate ~ 1 Gbyte/second**

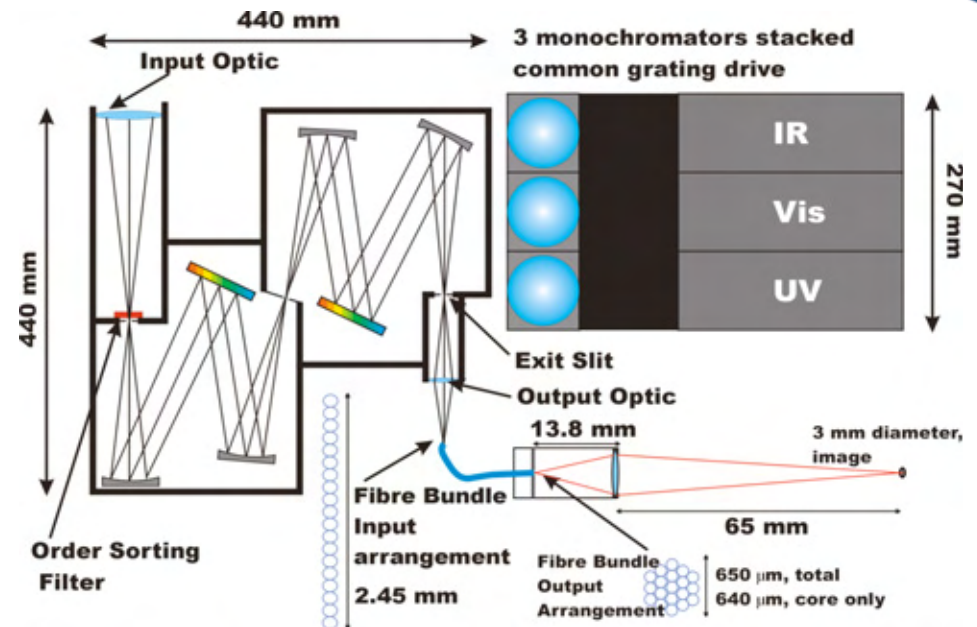
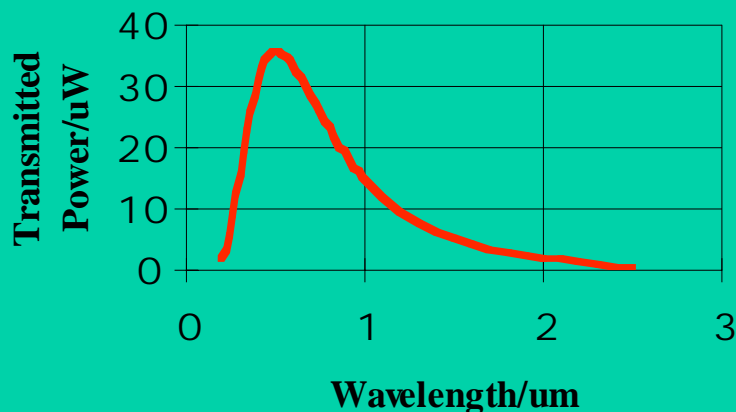
Design based on upgrade of ESA / APEX aircraft spectrometer
(could be “CHRIS2” or other imager)

4 independent filter radiometers measure s and p polarisation for

**atmospheric correction and to monitor TRUTHS EI using ground
targets for redundancy.**

Spectral Calibration Monochromator (SCM)

- Three separate double grating monochromators stacked and driven by a common drive shaft.
- Wavelength calibration via laser diode at input
 - Higher power for irradiance calibration

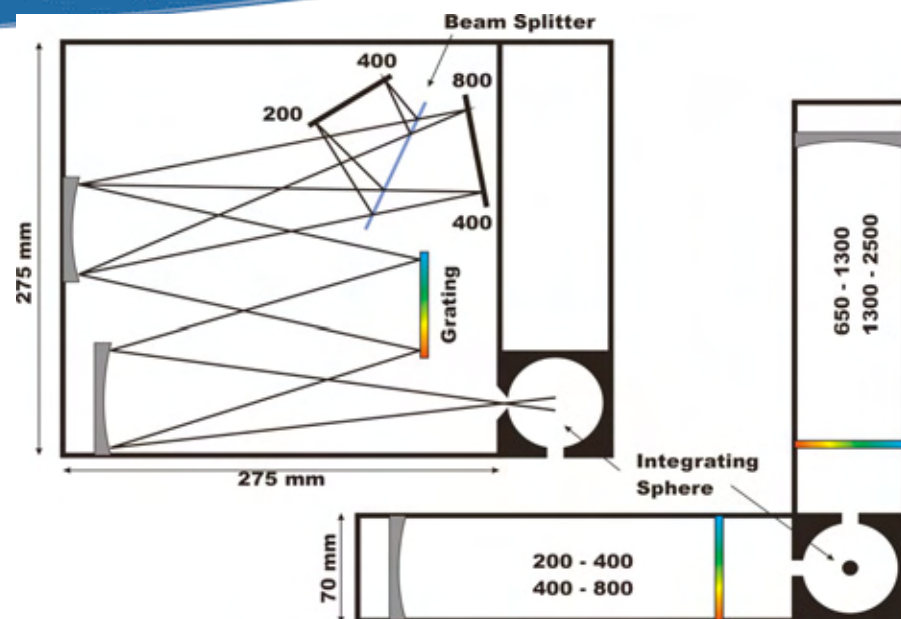


* Use of 3 separate fibre delivery systems allows throughput to be maximised.

* Transmitted power calculated using realistic commercial fibre, mirror and grating specifications, **now lab tested to check for micro-bending/movement issues.**

Solar Spectral Irradiance Monitor (SSIM)

(could be SIM of SORCE)



Spectral range: 200 to 2500 nm

Spectral resolution: 0.5 nm 200 – 1000 nm

1.0 nm 1000 – 2500 nm

Dynamic range: 0.001 – 5 Wm⁻² nm⁻¹

Temporal resolution: Variable

Accuracy: 0.1 %

Two single grating spectrometers

- Each utilising two “orders” via a beam splitter and two linear arrays

Solar input via a common integrating sphere diffuser and precision aperture

Transfer of calibration to global EO missions



- ◆ Establishment of reference data for Sun and Moon.
- ◆ In-orbit Comparison of solar viewing instruments e.g **SORCE**.
 - **Link to VIRGO of SOHO.**
- ◆ Establishment of network of Earth based Reference test sites.
 - **E.g Railroad Valley, Libyan Desert, Antarctica etc**
Sites to be characterised by field studies
 - **Instrumented with remotely controllable/readable monitors**
 - **Calibration coefficients updated regularly by TRUTHS satellite**
 - **Data accessible over WWW to allow reprocessing to suit individual satellite footprints and spectral characteristics**
 - **Improve accuracy of all sensors but particularly those with no on-board e.g. MSG, DCM ... reference for NPOESS etc minimising DATA GAPS!**
- ◆ **Simultaneous Nadir Overpass (SNO) with other sensors**
 - **additional use of Geo-stationary as monitors and transfer instruments**
- ◆ **Archived data reprocessable to improve historical reference.**
 - **Many in-flight sensors have the resolution, dynamic range and stability to allow update of calibration and viewed same desert targets.**
- ◆ **Targeted Science:** Surface BRDF, Carbon cycle, atmosphere, coastal zones



Summary

TRUTHS “International Standards laboratory in space” removes uncertainty due to storage, launch and degradation and its mission provides this benefit, together with SI traceability, to all other EO optical sensors in the solar spectral domain.

component of “ international calibration constellation” / CLARREO

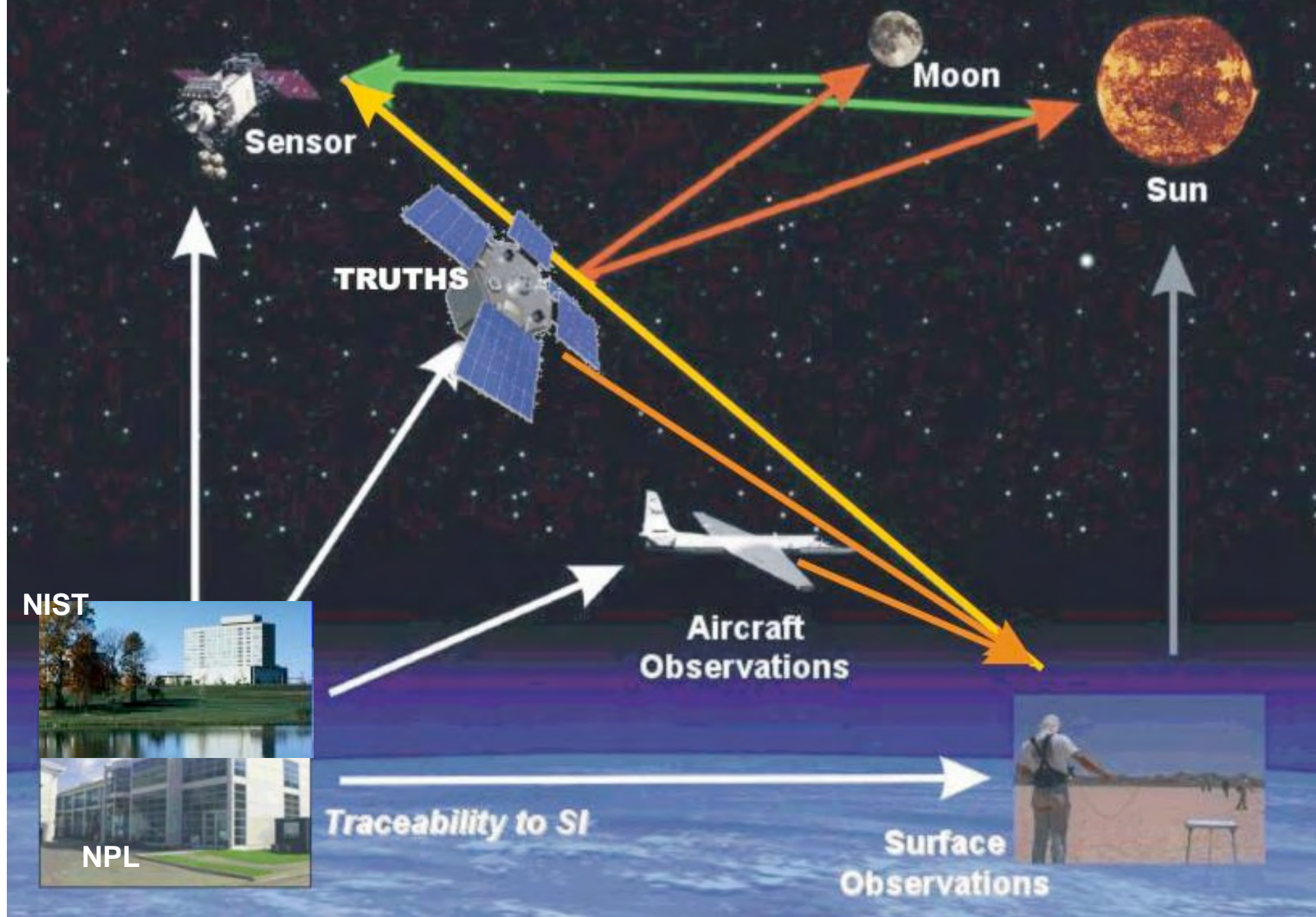
- Set of SI traceable reference targets: Sun, Moon, network of ground sites
- Utilises terrestrially implemented techniques and technology
 - In-flight calibration concept applicable to other missions
- Order of magnitude improvement in measurement accuracy
- Baseline for detection of climate change – reduce need for overlapping data sets
- Quality Assure data used by ‘decision makers’ and improve synergy between sensors
 - Tools to underpin GMES and GEOSS initiative
- Improved algorithms to allow quantitative measurement of bio-physical products
- Provide data to improve understanding of natural solar induced variation on climate and compare with anthropogenic effects.

The step change reduction in uncertainty and spin-off benefits is analogous to that obtained in NMIs when cryogenic radiometers were introduced in 1980s



Fox et al Adv in Space Physics 32 p2253 (2003)

Radiometric Measurement Strategy for Remote Sensing



International Requirements for TRUTHS (like) mission (history)

- CSAR - proposed to ESA (Eureca) ~1990 for TSI
- CSAR (ARMS) - “ ESA (space station) ~1997 for TSI
- TRUTHS - “ ESA (Earth Explorer opportunities) 2002

CSAR - Selected via peer review but needed national funding

TRUTHS – “To the best of the reviewers' knowledge, there is presently no strong need for absolutely accurate Earth spectral radiances since other errors dominate the radiometric error budgets of planned missions.” **Concept a little ahead of its time!**

- addressing needs of too many communities!!
- also did not provide sufficient clarity on transference to other sensors

Although ~~studies of this workshop~~ able to perform selected science at unprecedented accuracy

- principle aim is to make possible science of others
- is the key to truly operational data (GEOSS)
- essential reference as baseline for climate studies
- Ideally part of international effort

Benchmark calibrations from space: to meet key needs of climate and operational services such as weather

- WMO establish GSICS (Global Space based Inter Calibration System) – remit interoperability through traceability to SI) (2005/6)
- ASIC3 (Achieving satellite Instrument calibration for climate change) (2006)
 - US interagency workshop to establish national roadmap
 - Recommend 1/ establishment of joint agency calibration centre
2/ Satellite system to provide benchmark cals from space
- CEOS response to GCOS implementation plan (2006/7)
 - Satellite based mission to establish SI traceability in space
- National Academy of Sciences (decadal review) (2007)
 - CLARREO - **Climate Absolute Radiance and Refractivity Observatory**

to establish a “standards laboratory in space”

Agency and CEOS response to GGOS Requirements

CEOS WGCV response also
NASA (Don Anderson) to
priority 1 action A5

Action	Description	Lead expert	Team (Proposed Lead agency/ies in bold)
A-5	CEOS will plan by 2011 to make absolute, spectrally resolved measurements of radiance emitted and reflected by the Earth to space for information on variations in both climate forcings and responses.	Nigel Fox (NPL, chair of WGCV IVOS subgroup)	NASA, ESA, WGCV, NPL, NIST

Short-term objectives	Current status	Link to other GEO SBAs
Awareness and requirement study	There are currently several proposals for benchmark or absolute measurement of missions or payloads. Dr Fox has proposed the TRUTHS system. NIST proposed to establish absolute spectral irradiance measurements of the Moon for calibrating all solar reflective instruments. J. Anderson (Harvard U) has proposed a benchmark mission.	Energy, Weather

TRUTHS Mission – instrument breakdown

Core calibration unit: - Cryogenic Solar Absolute Radiometer (CSAR)

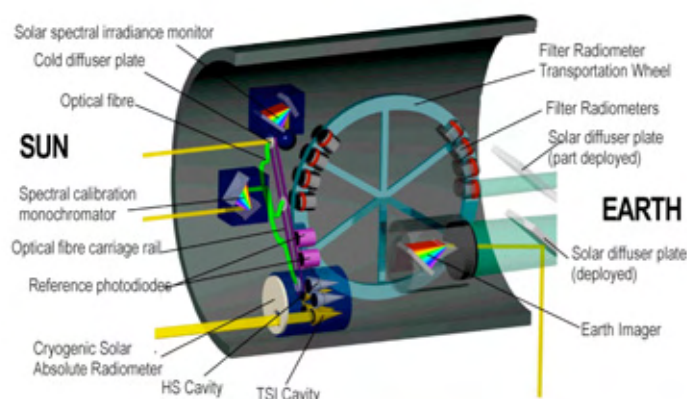
- Total solar irradiance
- Primary standard

- Spectral Calibration Source (SCS)

- spectral range to suit

- Filter Radiometers (FR)

- number and spectral range to suit
- Ground + atmosphere radiance (single pixel)



TRUTHS – LITE (Limited Implementation Technology Evaluator)

- Core calibration unit
- DMC like imager (few bands) (www.sstl.co.uk)
 - reference for Landsat bands and demo of principle
- *Optional Solar spectral irradiance*

TRUTHS Instruments: status / options

CSAR – Engineering model / ground demo currently funded and under development between PMOD WRC (Davos) and NPL (Dti)

- Space version funded by Swiss when flight opportunity confirmed

Spectral Calibration system / Filter Radiometers

- Techniques proven on the ground & instrumentation proven in space
- SSTL, RAL, MSSSL with NPL input, or other

Imager – CHRIS 2, DMC (lite), (non-UK)

Solar Spectral Irradiance – Linear array based spectrometer

- SSTL, MSSSL, RAL (space science?)
- SIM from US

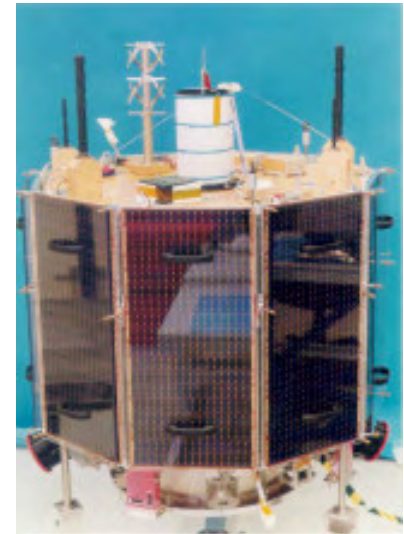
Platform and Launch

- **Baseline** (for first one)
 - Independent dedicated mission and launch
 - SSTL fully flexible platform ~ £6.5M
 - Primary launch ~ £3.5M
- Possible options
 - Piggyback on SSTL platform (DMC)
 - Share US or other platform
 - Shared cost (ESA? Other international ?)

Launch readiness: ~ 3 yrs to flight

SSTL platform capabilities:

- Payload ~ 200 Kg
- pointing accuracy ~ 0.04° ~ 500 m
- Slew rate ~ 0.5°/s



Next steps ?

- **Current activities**
 - NPL and PMOD WRC continue development of CSAR as engineering model for TRUTHS - Funded
 - Promotion / selected participation in international studies
 - BNSC looking at how to support project
- **Establish funded Flight opportunity**
 - **Mission study**
 - Technical scope (instruments / spectral range ...)
 - Operational benefits (GMES/GEOSS/CEOS/WMO/DMC)
 - Science objectives / priorities (NERC opportunities)
 - Development plan (collaborations)
 - **UK/EU funded mission**
 - BNSC
 - NERC
 - DEFRA
 - Dti
 - ESA
 - EUMETSAT
 - **UK collaborative mission (CLARREO?) or other**
 - Indication of potential support from BNSC
 - Partnership with SSTL
 - EU metrology programme (2009?)